Z’ gauge bosons at the Tevatron

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Outline

- Introduction: Why a new force?
- Theoretical framework
  - particle spectrum, couplings to fermions, anomaly cancellations
  - bounds on Z-Z' mixing
- Model-lines
  - Generalization of well-known E_6 models
  - New limits from LEP II searches
- Z' searches at the Tevatron
  - A new strategy: a bridge between modelers and Experimenters
  - dealing with higher order corrections
  - prospects for Z' searches
  - comparison with new LEP results
- Outlook

Why new gauge bosons?

- The SM → the pillar of particle physics: is based on local gauge invariance under $SU(3)_C \times SU(2)_W \times U(1)_Y$

  * however, its only an effective theory!

  * many open questions → demand physics beyond the SM

- It is natural to ask:

Are these all of the fundamental interactions of nature?

What are the limits on more? (LEP, Tevatron, future colliders)

- Many interesting theoretical models with extra gauge bosons.
  - **GUT**s with “large” gauge groups (*S0(10)*, E_6, …)
  - **Extra dimensions** with bulk gauge fields have massive copies of γ,Z
  - Theories like Topcolor use them to drive **EWSB**.
  - The **little Higgs** theories use massive vector particles to cancel quadratic divergences in the Higgs mass induced by W and Z.
  - New **SUSY** theories use them to survive the LEP II bound on $\mathbf{m_h}$.

Theoretical Framework

- New gauge boson Z': characterized by its mass and couplings
  ➡ Lagrangian constrained by gauge and lorentz invariance
- We extend the SM: *$SU(3)_C$ x $SU(2)_W$ x $U(1)_Y$ x* ***$U(1)_Z$***.
  neutral gauge bosons : W_3^μ, $\mathrm{B}_\mathrm{Y}^\mu$, $\mathrm{B}_\mathrm{Z}^\mu$ and gauge couplings g, $\mathrm{g_y}$, $\mathrm{g_Z}$
- Scalar sector responsable for EWSB includes:
  ➡ 1 or 2 Higgs-doublet(s) + a new scalar Φ
  $\mathrm{H_1, H_2} \Rightarrow \tan\beta = \mathrm{v_2 / v_1}$ $\qquad$ $\langle\phi\rangle = \mathrm{v}_\phi$ and neutral under SM
  with z_{H_1}, z_{H_2}, z_ϕ charges under $\mathrm{U(1)_Z}$

After diagonalizing the mass matrix → 3 physical states: a photon, a Z and a Z'

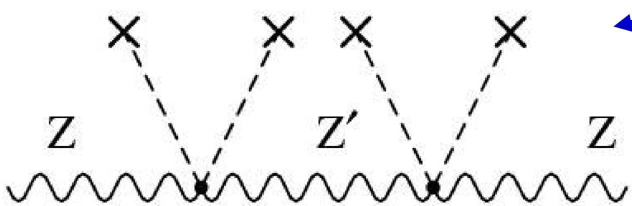
$$\mathrm{M_Z^2} = (g^2/4\cos^2_{\vartheta_W})\times(\mathrm{v_{H_1}^2} + \mathrm{v_{H_2}^2})[1+O(\varepsilon^2)]$$

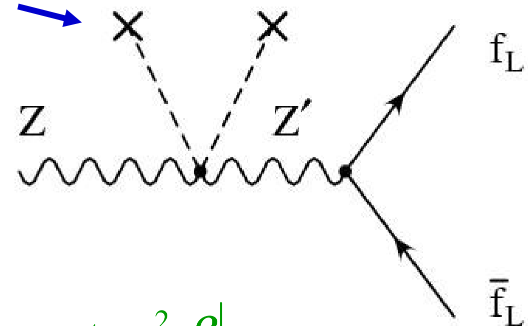
$$\mathrm{M_{Z'}^2} = (g_Z^2/4)\times(\mathrm{z}_{H_1}^2\mathrm{v_{H_1}^2} + \mathrm{z_{H_2}^2 v_{H_2}^2} + z_\phi^2\,\mathrm{v}_\phi^2)[1+O(\varepsilon^2)]$$

with ε → mixing angle between the SM Z and $\mathrm{B_Z^\mu}$

e^+e^- Limits: Z-Z' Mixing

- Precision measurements of Z physics
  - SM predictions in agreement at roughly few per mil level.
  - A Z' which mixed with Z would distort these predictions





→ hence, it requires: $\varepsilon \approx \frac{g_z}{g}\left(\frac{\cos\theta_W}{M_{Z'}^2/M_Z^2 - 1}\right)\frac{\left|z_{H_1} + z_{H_2}\tan^2\beta\right|}{1+\tan^2\beta} \le 10^{-3}$

– A Z' accesible at the Tevatron needs $g_Z \approx O(1)$ and $M_{Z'} \approx 0.2 -- 0.7$ TeV

hence LEP bounds imply: $\varepsilon \approx z_{H_1}\cot^2\beta + z_{H_2} << 1$

There must be a fine-tuning

or else → $z_{H_2} << 1$ and $z_{H_1} << 1$ or $\tan\beta >> 1$

Z' boson couplings to Fermions

$$L \to \sum_f z_f \, g_Z \, Z'_\mu \, \bar{f}\gamma^\mu f \qquad f = e_R, l_L, u_R, d_R, q_L$$
$$(\times 3\ generations) \Rightarrow 15\ \mathrm{z_f}'s$$

To obtain masses and mixing angles:

- **z_f restricted from Yukawa interactions:**

<u>Quarks</u>: generation independent $U(1)_Z$ charges and

$$z_u = z_d = z_q \quad (\mathrm{z_H} = 0) \quad \text{or} \quad z_u = z_q \ \text{ and } \ z_q - z_d = z_{H_1}$$

<u>Charged Leptons</u> : can be gen. dependent $\quad z_l = z_e \ \text{ or } \ z_l - z_e = z_{H_1}$

<u>Neutrinos</u> : depend a lot on assuming right-h. neutrinos , gen. Yukawas from higher dimensional operators in powers of $\phi/\mathrm{M_{heavy}}$, extra scalars.

- **$SU(2)_W$ invariance:** $z_{\mathrm{u_L}} = z_{\mathrm{d_L}}$ and $z_{\mathrm{e_L}} = z_{\nu_\mathrm{L}}$
- **FCNC:** avoided assuming family univ. in the quark sector. None in
- the charged lepton sector.

Assuming that Z' decays mainly into SM particles: Z' properties determined by

$$\mathrm{M_{Z'}}\,,\ \Gamma_{\mathrm{Z'}}\,,\ (z_{l_j}, z_{e_j}, z_q, z_u, z_d) \times g_Z$$

Anomaly cancellations

- Additional restrictions on U(1)z charges from gauge anomaly cancel.

$$[SU(3)_C]^2\, U(1)_Z \to A_{33Z} = 3(2z_q - z_u - z_d) \qquad [SU(2)_W]^2\, U(1)_Z \to A_{22Z} = 9z_q + \sum_{j=1}^{3} z_{l_j}$$

$$[U(1)_Y]^2\, U(1)_Z \to A_{11Z} = 2z_q - 16z_u - 4z_d + 2\sum_{j=1}^{3}\left(z_{l_j} - 2z_{e_j}\right)$$

$$[U(1)_Z]^2\, U(1)_Y \to A_{1ZZ} = 6(z_q^2 - 2z_u^2 + z_d^2) - 2\sum_{j=1}^{3}\left(z_{l_j}^2 - 2z_{e_j}^2\right)$$

$$[U(1)_Z]^3 \to A_{ZZZ} = 9(2z_q^3 - z_u^3 - z_d^3) + \sum_{j=1}^{3}\left(2z_{l_j}^3 - z_{e_j}^3\right) - \sum_{i=1}^{n} z_{\nu_i}^3$$

Finding solutions for these Eqs.is non-trivial!

GCI + gauge inv. $\Rightarrow A_{GGG} = 9(2z_q - z_u - z_d) + \sum_{j=1}^{3}\left(2z_{l_j} - z_{e_j}\right) - \sum_{i=1}^{n} z_{\nu_i}$

Possible solutions:

- Eqs. + mass gen. via Yukawas $\Rightarrow U(1)_{B-L}$ (gen indep. q+l or just q)
- New Fermions + gen. indep. charges with Yukawa mass terms $\Rightarrow U(1)_{B-xL}$
- Gen. indep. charge assignment but no restriction from Yukawa mass terms $\Rightarrow U(1)_{q+xu}$ certain values of x yield B-L, $U(1)_\chi$ of SO(10),...
- Both restrictions: yukawa mass terms + new fermions SM charged
  - $U(1)_{d-xu} \Rightarrow U(1)_I$ of E_6 $(x=0)$
  - $U(1)_{10+x\bar{5}} \Rightarrow U(1)_\psi, U(1)_\eta, U(1)_\chi$ $(x=1,-1/2,-3)$

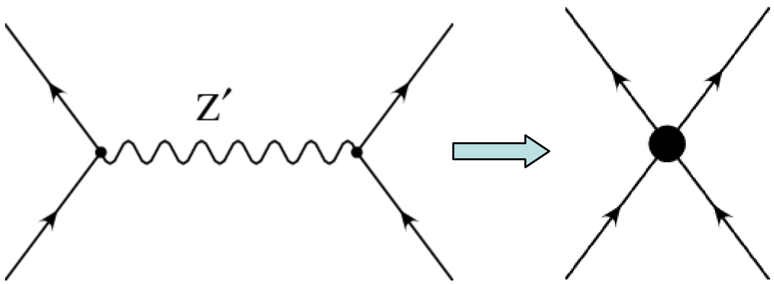
Specific "Model-lines": fermion gauge charges

	$B-xL$	$q+xu$	$10+x\bar{5}$	$d-xu$
$q_L=(u_L,d_L)$	$+1/3$	$+1/3$	$+1/3$	0
u_R	$+1/3$	$+x/3$	$-1/3$	$-x/3$
d_R	$+1/3$	$(2-x)/3$	$-x/3$	$+1/3$
$l_L=(e_L,\nu_L)$	$-x$	-1	$+x/3$	$(x-1)/3$
e_R	$-x$	$-(2+x)/3$	$-1/3$	$+x/3$

- Subject to theoretical motivations, we find a set of 4 "model lines".
- Each has a free parameter, x, specifying all of the couplings of the Z'.
- The $\mathbf{E_6}$ Z's are certain values of x for certain model lines.
- All model lines except $U(1)_{q+xu}$ demand new fermions

Z' searches at LEP II

- Searching for new physics in $e^+e^- \to f\,\bar{f}$
  - At $\sqrt{s} \ll M_{Z'}$, the Z' effects look like four fermion interactions:



  - These depend quite sensitively on
    the chiral structure of the Z' couplings to e, and also to other fermions.

- Comparing LEP limits in their contact interactions formalism with operators of the same structure in the Z' theory:

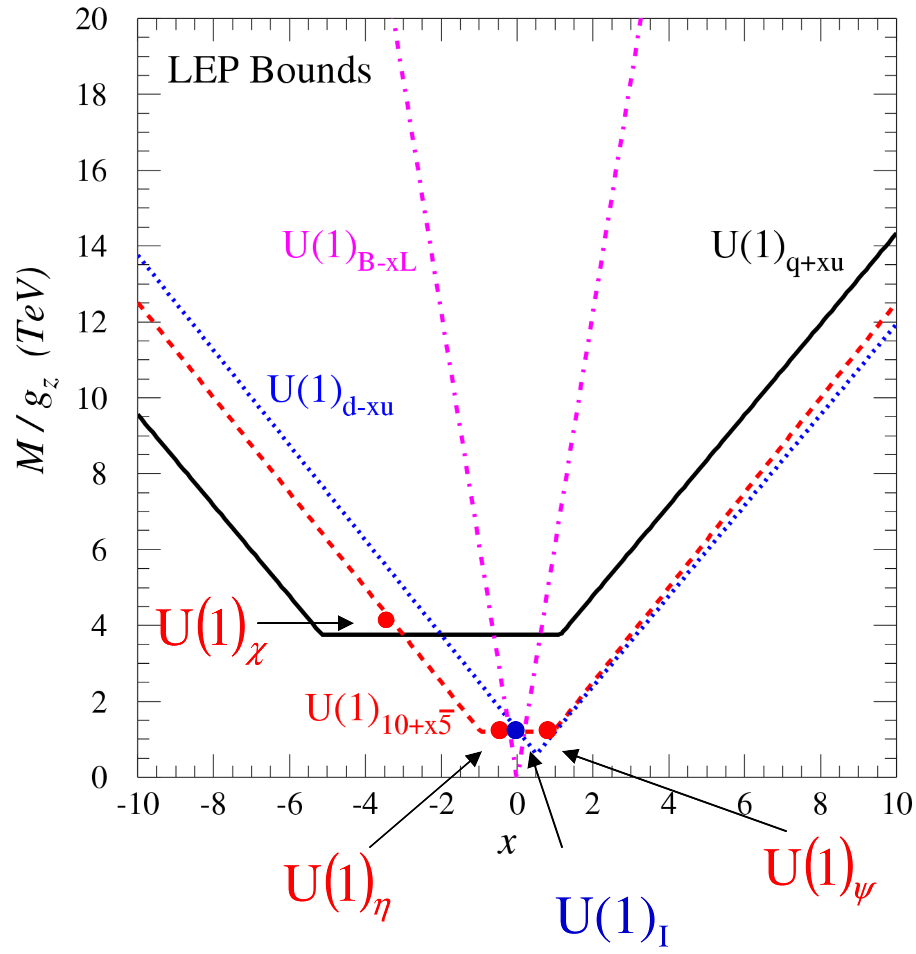
$$M_{Z'}^2 - s \geq \frac{g_z^2}{4\pi} \left| z_{e_A} z_{f_B} \right| \left(\Lambda_{AB}^{f\pm} \right)^2 \longrightarrow M_{Z'} \geq |z| g_z \times (\text{a few TeV})$$

- LEP-II has searched for evidence of contact interactions in almost all conceivable channels.
- Bounds vary from channel to channel, complicating the analysis.

For example: $U(1)_{B-xL}$ has vector-like interactions with quarks and leptons

→ strongest bound : $e^+e^- \to l^+l^- \Rightarrow \Lambda^+_{VV} \geq 21.7\ \mathrm{TeV}$ → $M_{Z'} \geq |x| g_z \times 6\ \mathrm{TeV}$

In general, the best bound is x dependent: scan all channels for fixed x and choose the best:

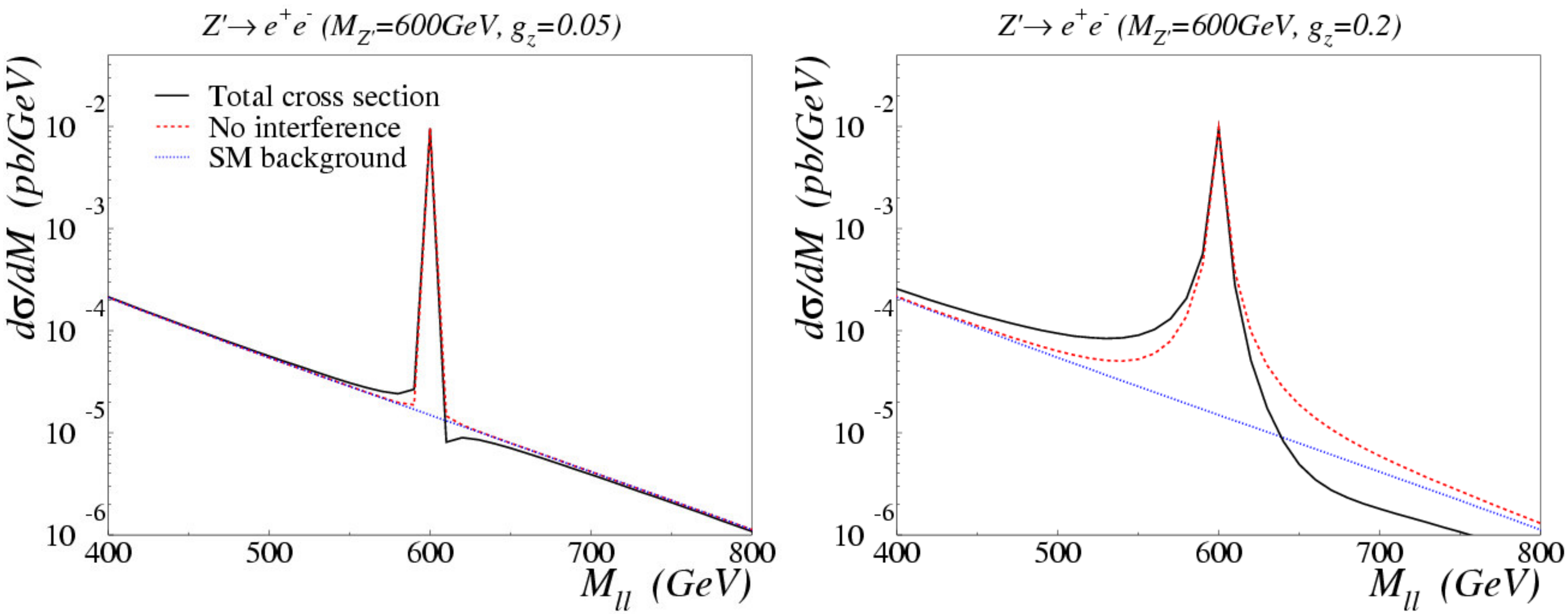


Lower bounds on $M_{Z'}/g_Z$ from LEP II searches for LL, RR, LR, RL contact int. (VV for $U(1)_{B-xL}$) for our model lines as a function of x.

for most points there is no dedicated analyses from LEP!

Z' Searches at the Tevatron

- Hadron colliders look for Z's most effectively in the decay into charged leptons (**e±, μ±, τ±**).
- Unlike LEP, hadron colliders are sensitive to Z's which do not couple to **e±** : unexplored territory!
- The signal appears as a resonance above the (smooth) lepton pair backgrounds. Interference effects are tiny.



- Run I and existing Run II analyses have presented limits on σ x BR. Specific $\mathbf{E_6}$ models are usually overlaid to illustrate the results.
  - This is good because σ x BR is fairly model-independent:

  ⟹ results can in principle be applied to other theories with Z's.
  - However, it is inconvenient since computing a hadronic cross section is not a completely trivial task : one has to know about QCD, PDFs, ...

  ⟹ are important, but have nothing to do with specific Z's properties.
- Alternate approach: factor out the universal QCD dep., and bound only the Z' quantities themselves.

<u>In the narrow width approx.:</u>

all QCD dep. + Z' couplings to quarks

$$\sigma\left(p\bar{p} \to Z'X \to l^+l^-X\right) = \frac{\pi}{48s} W_{Z'}\left(s, M_{Z'}^2\right) \; Br\left(Z' \to l^+l^-\right)$$

- **for any neutral gauge boson with generation indep couplings to quarks**

$$W_{Z'}\left(s, M_{Z'}^2\right) = g_Z^2 \left[\left(z_q^2 + z_u^2\right) w_u\left(s, M_{Z'}^2\right) + \left(z_q^2 + z_d^2\right) w_d\left(s, M_{Z'}^2\right)\right]$$

Model independent, contain PDF's and depend on Z' mass only

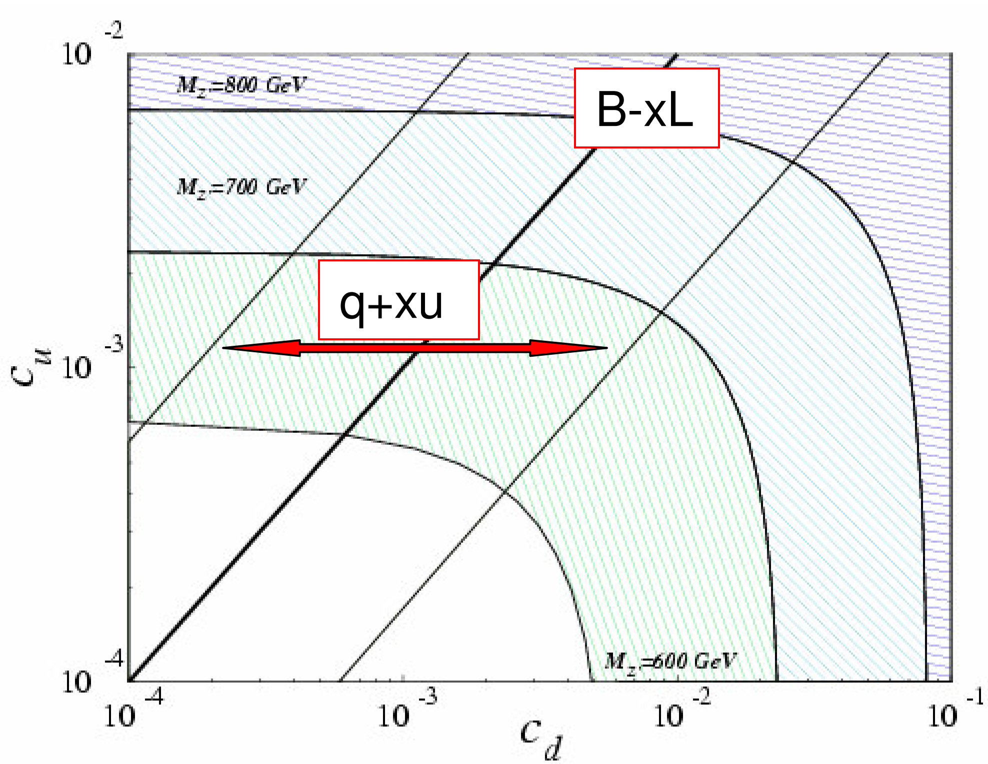
We define coefficients which contain all the dependence on Z' couplings to quarks and leptons:

$$c_{u,d} = g_Z^2 \left(z_q^2 + z_{u,d}^2\right)\ \mathrm{Br}\left(Z' \to l^+ l^-\right)$$

→ this parametrization allows direct extraction of bounds on $c_{u,d}$ plane from experimental limits on $\sigma \times \mathrm{Br} = (\pi / 48s)\left(c_u w_u + c_d w_d\right)$

- Allows easy comparison of exp. bounds with predictions from Z' models
- Provides common ground between theory and experiment

(no need to compute hadroproduction cross section)



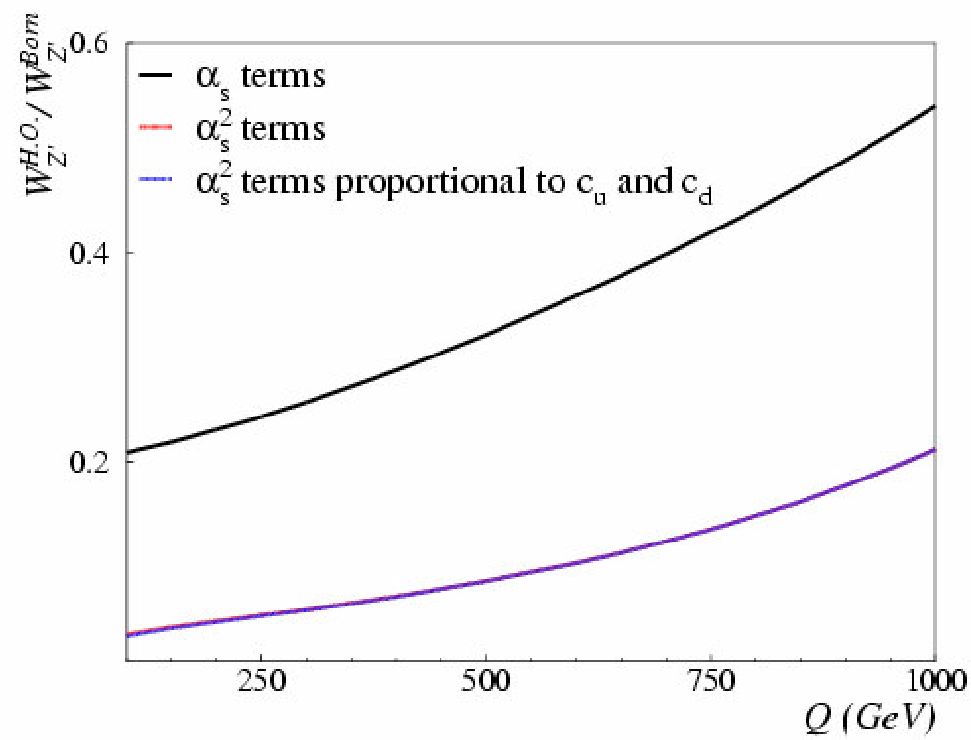
CDF 95% C.L. exclusion limits on $\sigma\left(p\bar{p} \to Z'X \to l^+ l^- X\right)$ for different Z' mass values in the c_u-c_d plane

$\boxed{10 + x\bar{5}}$ models are constrained to the region $c_u \leq 2c_d$

No constraints for $\boxed{d - xu}$ models.

Comments on higher order corrections

- **Robustness of our parametrization**



→ At LO and NLO in QCD is works perfectly well

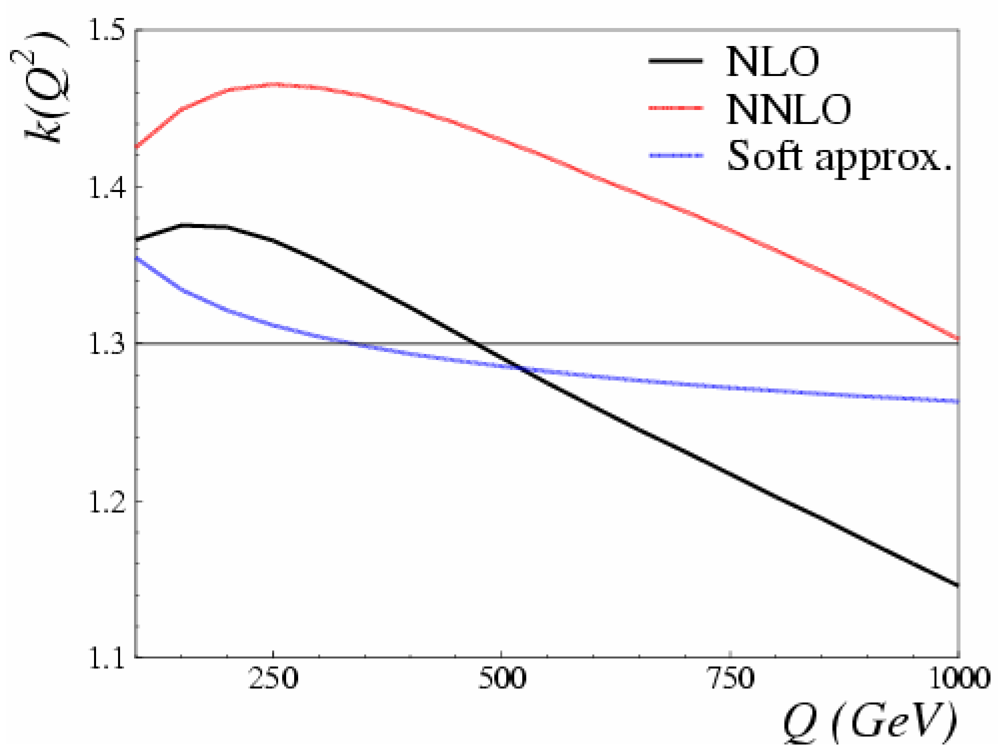
→ At NNLO : dep. on combination of couplings beyond $\left(z_q^2 + z_{u,d}^2\right)$, but still parametrization in terms of $c_{u,d}$ is an excellent approximation.

Dominant NLO EW corrections are model-independent (and probably important at the few % level).

- **K- Factors**

$$k_{\mathrm{N^iLO}} = W_{Z'}^{\mathrm{N}^i\mathrm{LO}} \Big/ W_{Z'}^{\mathrm{LO}}$$

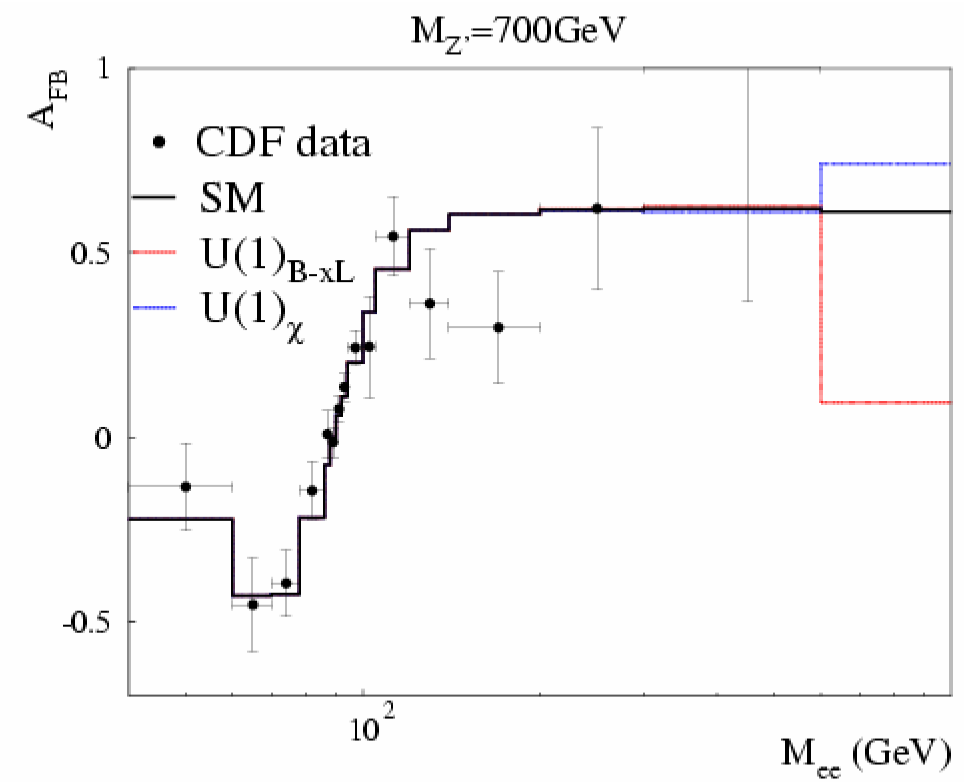
→ **Ratio of the h.o. results over LO one**



Strong variation with the invariant mass of the lepton pair Q

Angular distribution of the final lepton pair

- Is highly model dependent and can be a tool to discriminate between models in case of discovery.



Foward-backward Asymmetry at LO with $M_{Z'}$ = 700 GeV for B-L and g_Z=0.1 for d-u and g_Z=0.5

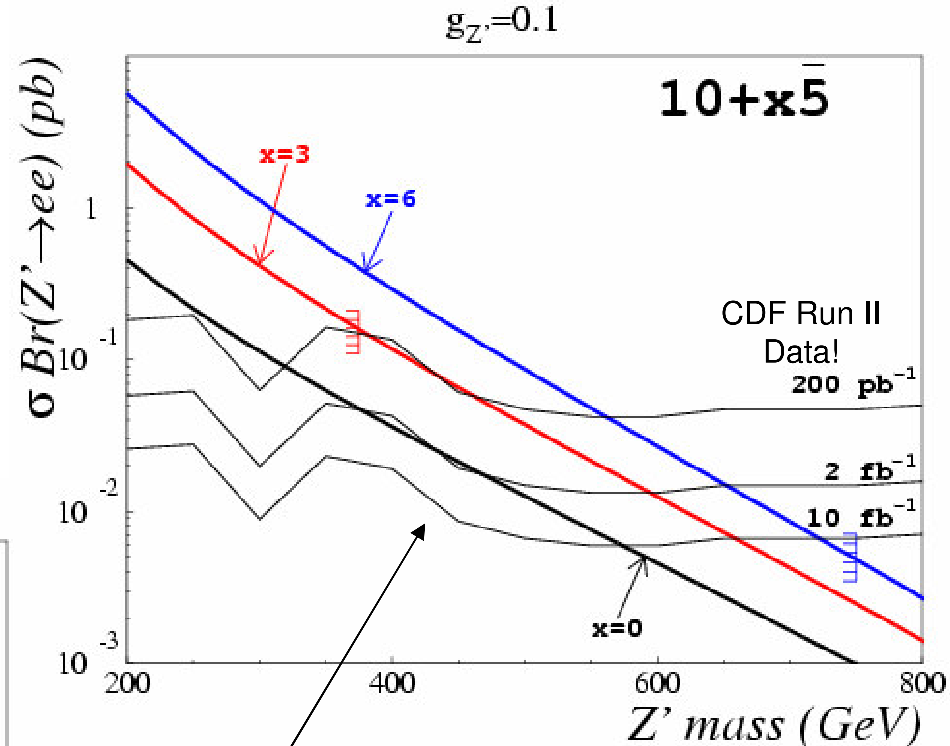
Comparison with SM prediction and CDF data

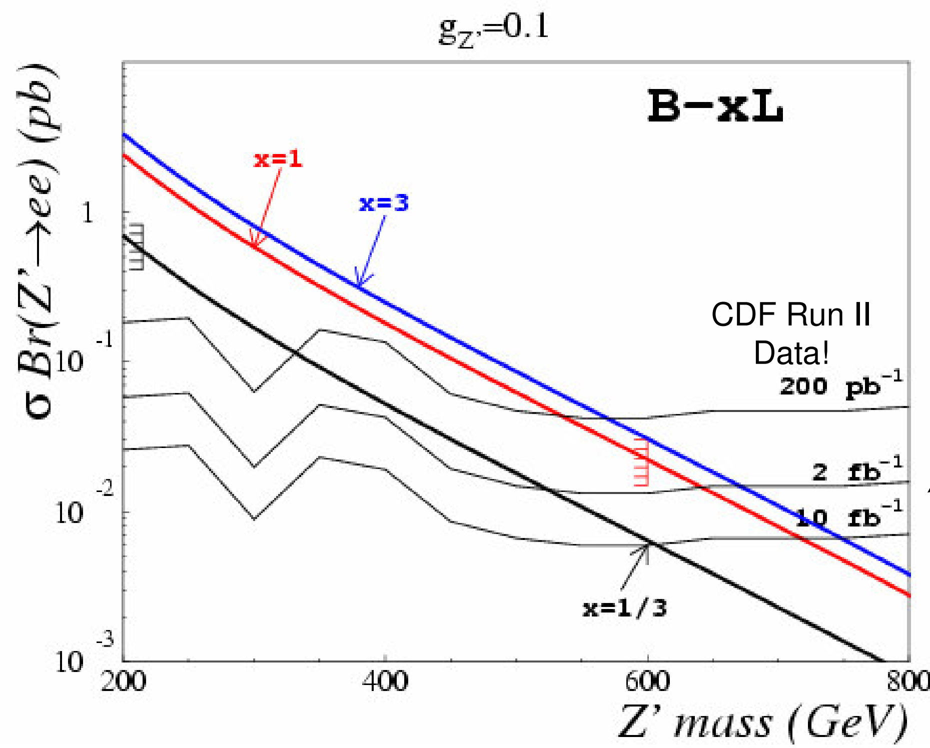
A_{FB} shift with respect to SM one in these models has opposite sign: it may be possible to distinguish between them with enough statistics in the high mass region

Prospects for Z' Searches at the Tevatron

- CDF and D0 will explore new regions in masses and couplings of Z' models, with chance for discovery!

- In case of no signal excess observed
→ set bounds on $M_{Z'}$ and g_z
or equiv. on c_u and c_d param. space

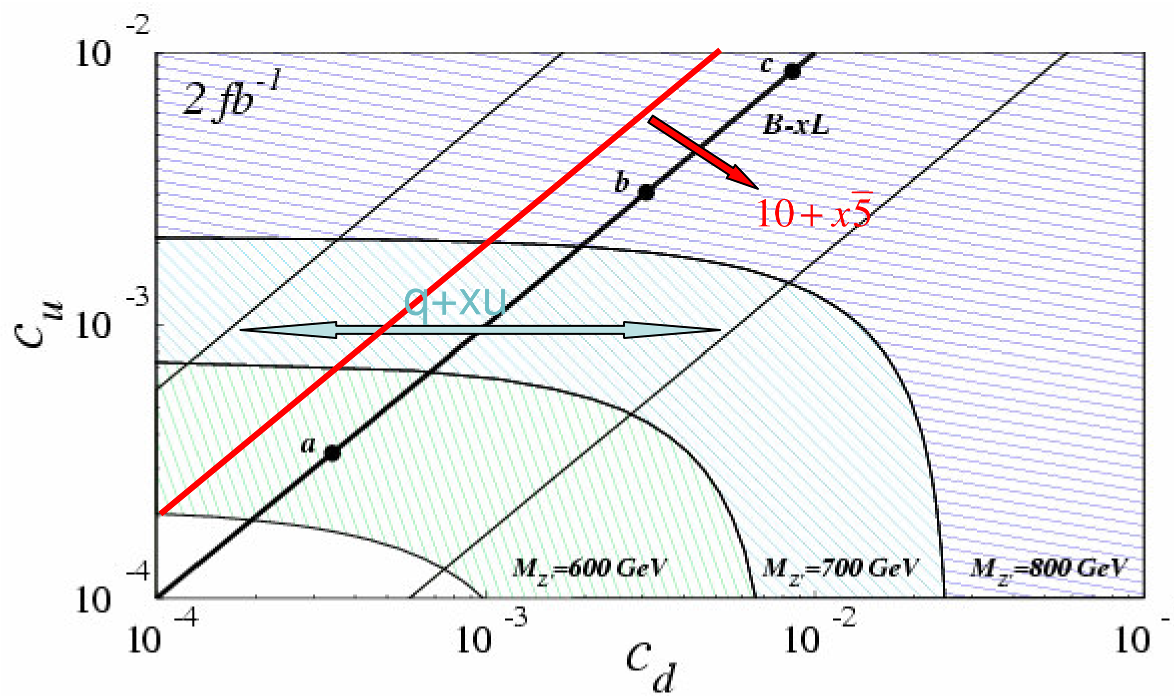




Projections scaled by √L

Vertical marks show current LEP bounds on Z' mass from contact interactions.
→ sizable unexplored regions that the Tevatron can probe!!

Tevatron projected excluded regions in c_u-c_d plane



→ the dots labeled a,b,c correspond to B-L for g_Z= 0.1, 0.2, 05.

- Z' properties are primarily described by $M_{Z'}$, $\Gamma_{Z'}$ and Z'-fermion couplings
- The exclusion curves above place a bound on a single combination of these param.

In any specific model defined by certain fermion charges

→ compute c_u and c_d and derive the limit on the gauge coupling g_Z as a function of $M_{Z'}$

Outlook

- Neutral massive gauge bosons, Z’s, naturally appear in many models of new physics
- e+e- colliders have placed strong constraints on Z-Z’ mixing

  → EWSB Higgs must be neutral under the new symmetry or some fine-tuning required

- We derive model-lines that generalize previous E_6 models
- We propose a new strategy to bound quantities which involve the Z’ properties, independent of QCD quantities
- This facilitates enormously the comparison between data and any given model!!

  → We present for the first time the LEP bounds on the general class of Z’ models

Our results provide a unique common ground for experimenters and model builders, useful both for the Tevatron and the LHC.